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**** SMALL ENTITY ****

Title

Monolithic photoreceiver array technology for free space optical networks

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1. TECHNICAL APPROACH

1.1 Background/Scope/Program Objectives

Epitaxial Technologies will develop an ultra sensitive, monolithic photoreceiver array for the Terahertz Optical Reachback (THOR) networks. The proposed monolithic photoreceiver array will be based on unique semiconductor optical amplifier and optical conversion technologies developed by the Company, which will be deployed to realize on a single chip all the components required for the ultra sensitive photoreceivers for the THOR communications network. This is a technology maturation effort that will enable the components and systems for the THOR network to be more manufacturable and affordable, thus allowing the network to rapidly expand from the demonstration stage into all parts of the DoD Global Grid. The developed monolithic photoreceivers will have sensitivities as low as –47 dBm (62 photons/bit at 2.5 Gb/s) with low power consumption and with sizes and form factors that will be at least an order of magnitude lower than possible with commercial-off-the-shelf (COTs) components and that will fit into the limited space of a UAV.

The DoD needs to provide the US warfighters with assured and secure information anywhere, at any time and in the right form[1,2]. As a result, DoD has been developing the Global Information Grid architecture, which will do this by providing data to US military forces worldwide from remote UAVs to regional commanders and to, soldiers on the front line. In order for this vision to be fulfilled, the current National Information Infrastructure (NII) and Defense Information Infrastructure (DII) upon which DoD currently depends must be augmented or replaced by an extensible communication architecture that assures maximum connectivity among the current terrestrial networks, the battlefield, aircrafts, spacecrafts, UAVs, ships and submarines.

The THOR program aims to provide the communications infrastructure upon which the DoD global grid relies. It will do for mobile military computing and communications platforms what DARPA's ARPANET did for fixed computing networks with the Internet. The THOR network will need at the most basic physical layer level, powerful and efficient optical transmitters, as well as ultra sensitive photoreceivers to achieve the greatest range and highest bit rate. Although these requirements can be met using COTs for the initial operational demonstrations, DoD wide deployment of the THOR network will require paradigm shifts in the development and production of optical networking devices and components. The needed paradigm shifts for DoD wide deployment of the THOR network can only be implemented through specific technology maturation efforts that will minimize the size, weight and power as well as system cost while meeting network link requirements affordably.

One of the critical areas where there will be the most need for technology maturation is the photoreceiver. Ultra sensitive photoreceivers will reduce transmitter requirements and will be key to maximizing bit rates and link distances. Because the potentially incident network optical radiation can be as low as –40 dBm (100 nW), the notional THOR network requires photoreceivers with sensitivities as low as -47 dBm. The most sensitive photoreceivers demonstrated to-date have been based on optically preamplified direct-detection receivers. The block diagram of such a receiver is shown in Figure 1.1. It consists of an erbium doped fiber amplifier, EDFA, a Bragg filter, a photodiode detector followed by electronic amplifiers and filters. Sensitivities as low as 52 photons per bit (ppb) or -42 dBm at a bit error rate (ber) of 10^{-9} have been recently demonstrated using this approach at 10 Gb/s[3,4]. While they may be adequate

for the initial THOR network demonstration, EDFA based photoreceivers have several disadvantages if they are used for the DoD wide deployment of the THOR network. First, they are based on disparate components connected together. This will result in larger than desired receiver equipment with footprints and form factors that may not be suitable for the spatially limited environments of aircrafts, satellites and submarines. Second, the best in class performance demonstrated so far may not be possible under the rigors of large quantity production. This is especially true for the EDFA, which suffers from severe dimensional and manufacturing tolerances that will degrade its performance, thereby reducing the receiver sensitivity. In addition, it is not possible to implement receiver arrays with this technique. Finally, the cost of such a system, particularly that of the EDFA will be inordinately high.

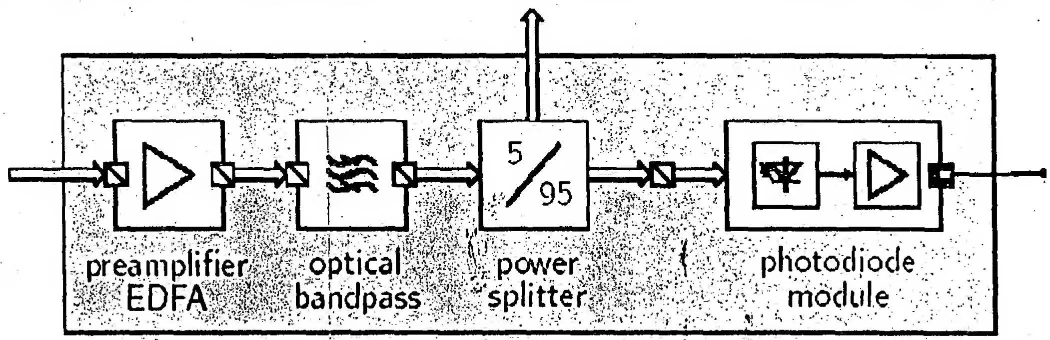

Figure 1.1 Block diagram of an optically preamplified, direct detection amplifier

Clearly, techniques are needed for producing for the THOR network, photoreceivers that are sensitive, compact and affordable. An approach to meet this challenge is to monolithically integrate as many of the components in Figure 1.1 as possible. While monolithic integration of the back end of Figure 1.1 in the form of integrated photoreceivers chips have been demonstrated, the highest conversion gain of 1500 V/W is still lower than required for the THOR receiver link budget (2800 V/W) [(5)]. As a result, potentially available integrated diode photoreceivers will still need to be combined with several additional components including the EDFA amplifier, the optical band pass filter and a TIA amplifier after the diode photoreceiver.

Therefore, it can be concluded that the kind of fully monolithically integrated ultra sensitive photoreceiver required for the THOR network that is compact and affordable is currently not available. Epitaxial Technologies proposes an approach for monolithically integrating on a single chip, all the components of the photoreceiver shown in Figure 1.1 such as the optical amplifier, the optical bandpass filter and the photodiode module. The Company will monolithically integrate a VCSEL optical preamplifier with a photodiode receiver and related amplifiers and filters on the same chip as shown in Figure 1.2 to replace all the components in Figure 1.1. Use of a VCSEL optical preamplifier in place of a fiber preamplifier or a standard semiconductor laser preamplifier will enable improved optical coupling, lower noise and power consumption and low manufacturing cost for THOR network components. In addition the VCSEL has an integral Bragg filter, there is no need for the optical bandpass filter. Also, the proposed approach will reduce the photoreceiver footprint by orders of magnitude as shown in Figure 1.3. This is particularly important for the cramped interior of a UAV where low power consumption and small sizes and form factors are critical requirements.

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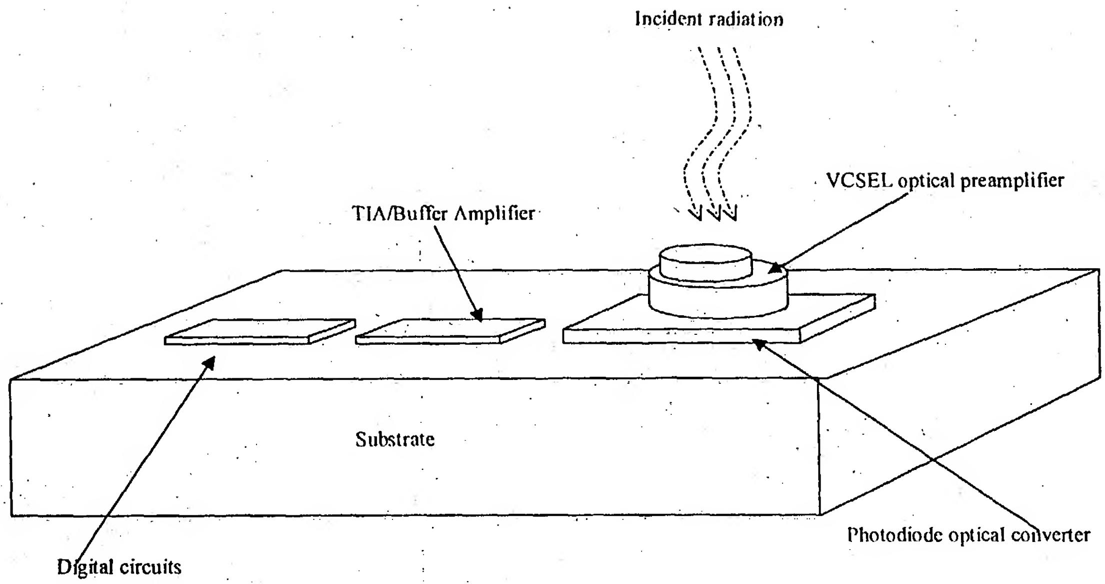
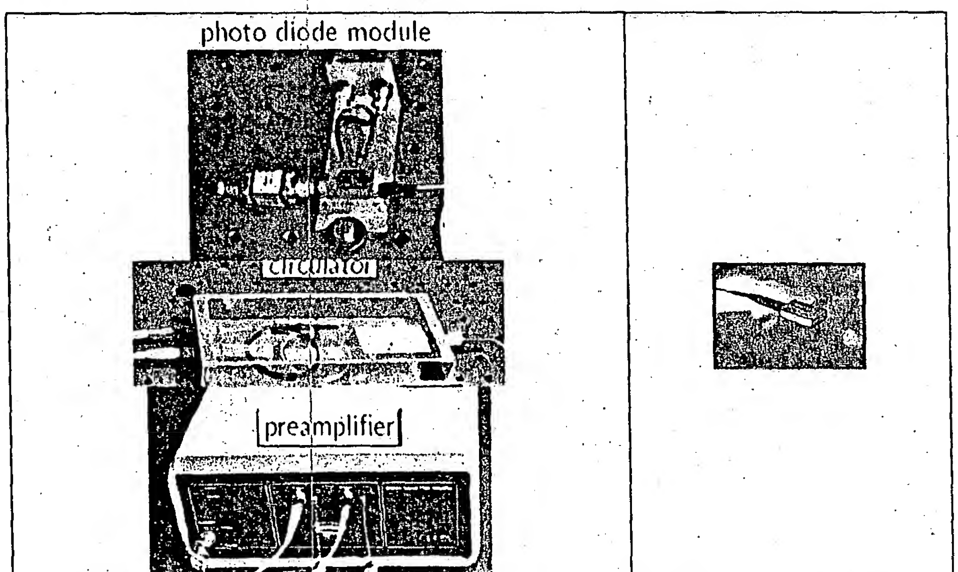


Figure 1.2 Conceptual sketch of ultra sensitive monolithic photoreceiver



a. Current technology b. Proposed technology

Figure 1.3 Footprint reduction of proposed ultra sensitive monolithic photoreceiver

The proposed monolithic photoreceiver will be based on two technologies: a long wavelength VCSEL technology and a resonant bipolar transistor (RTBT) technology that have been developed by Epitaxial Technologies and that can both be used to populate a chip with optical preamplifiers, filters, photodiode arrays, rf oscillators and baseband rf amplifiers. The VCSEL technology will enable easy acquisition and low power optical preamplification of the incident beam in a THOR network. The RTBT technology will enable easy and manufacturable on-chip integration of the optical preamplifier with the optical conversion elements and the associated electronic components that will ensure ultra high sensitivity.

During the first phase of the THOR program, we will optimize the two technologies to produce components that exactly meet the requirements of the THOR network. At the end of this phase,

we will design a monolithic photoreceiver. During this phase, we will also liaison and work with the THOR program companies who are involved in the network architecture aspects to make sure our photoreceiver designs are compatible with their network system requirements. During the next phase, we will team with one of these program participants to produce monolithic photoreceivers that they can deploy in the developed THOR network during the third phase and beyond. To fulfill this vision of developing and producing monolithic integrated photoreceiver arrays that are deployable in the THOR network, we will target the following objectives:

1. Demonstration of a 2.5 Gb/s, VCSEL optical preamplifier with 30 dB gain.
2. Demonstration of a 2.5 Gb/s, RTBT photodiode optical converter integrated with oscillator, mixer and baseband amplifier. The optical converter shall have a 2,500 V/W conversion gain at 2.5 Gb/s.
3. Design of a 2.5 Gb/s monolithic photoreceiver that will be directly deployable in the THOR network when produced during the second phase.
4. Development of a plan to ensure that this photoreceiver technology will be extensible to a wider network and higher bit rates when this becomes possible and necessary.

1.2 Program Plan

Epitaxial Technologies will demonstrate the key components for a monolithic ultrasensitive photoreceiver for the THOR network. We will use a unique approach to combine VCSEL optical preamplifiers with RTBT optical converters on the same chip. The effort will be carried out at the facilities of Epitaxial Technologies. However, for the design of the structures and to determine the alloy compositions, band gap discontinuities, and layer thicknesses, theoretical calculations will be undertaken as a consultant by Dr. A.F.M. Anwar of the University of Connecticut, who has extensive experience in the design of electronic and optical devices. In addition, Mr. Kenneth Vaccarro of AFRL/SNHC, who has the facility and experience in high speed optical device testing has agreed to collaborate in the optical testing of the photoreceiver components. To accomplish the objectives listed in Section 1.1, we will carry out the following tasks.

<u>Task1. Optimize and develop VCSEL optical preamplifiers</u>

Epitaxial Technologies will use an existing design for longwave VCSEL lasers for the optical preamplifier. Instead of the typical design for stimulated emission, it will be designed for amplified spontaneous emission. The design will be based on antimonide mirrors to minimize the number of mirror layers and GaInAs quantum well active layers for amplification of 1.55 µm radiation.

<u>Task 2.Optimize and develop RTBT optical converters</u>

The RTBT optical converters will be based on the Company's RTBT material technology that can be used to produce PIN photodiode detector and HBT amplifiers as well as resonant tunneling diodes for oscillators and switches. First, we will optimize the design of the RTD structure using an AlAsSb /AlInAsSb (barrier) and a GaInAs/GaInAs-InAs-GaInAs (well) material system, which will result in large peak-to-valley ratios (PVR) and high current density because of its large conduction band discontinuity (ΔE_c). We will optimize the layer thicknesses to achieve large PVR. Next, we will design heterojunction bipolar transistor (HBT) structures using the InP/GaAsSb/(GaInAs, InP) material system. Based on its ideal band line-up (ΔE_v = 0.78 eV and ΔE_c = -0.15 eV), this material system has the greatest potential for high-speed performance and high reliability. The thickness, doping and composition of the layers will be

selected to give the highest current cut-off frequencies and breakdown voltages. Finally, we will design the RTBT combining the optimized RTD and HBT structures.

Task 3. Fabricate and test VCSEL optical preamplifiers and RTBT optical converter elements.
We will fabricate and test individual photoreceiver elements that were developed during the previous tasks. In some cases we will use existing mask sets to fabricate the VCSEL preamplifier diodes and the RTDs and HBT devices in Epitaxial Technologies clean room facility, which is well equipped for processing devices and circuits. In other cases we will layout and create new mask sets to fabricate the RTBT photodiode detectors and amplifiers. We will test the photoreceiver elements to determine the optical gain and optical and electrical bandwidth of the VCSEL preamplifiers. We will also test the RTBT devices for power gains, current gains, peak-to-valley ratios, and optical conversion gain.

Task 4. Design ultrasensitive photoreceiver
Using data from Task 3, we will perform a preliminary design of the ultrasentive photoreceiver. In the design, we will trade-off the optical gains and noise performance of the optical preamplifier with that of the optical converter to investigate the compromise between ease of fabrication of each photoreceiver stage with the performance. For example, the thickness of the optical preamplifier structure can be reduced to minimize fabrication complexity at the expense of the optical gain. This optical gain penalty can then be compensated for in the design of the optical converter by adding additional electronic gain stages without compromising the producibility.

Task 5. Demonstrate that this is a flexible and extensible technology platform
The success of the proposed ultrasensitive photoreceiver will depend on the flexibility and extensibility of the technology used to produce it. Therefore for this task, we will investigate whether and how the technology can be used to produce photoreceivers that can cover longer ranges and larger networks and also to handle higher bit rates than 2.5 Gb/s, if and when this becomes possible and necessary. To do this, we will explore the limits of the photoreceiver bandwidths and sensitivity and how they can be enhanced without significant additional research and development efforts.

Task 6. Reporting
We will provide AFRL/SNKD and DARPA with monthly project reports and a final report detailing the technical activities and the accomplishments for the project.

Task 7. Technical meetings
Epitaxial Technologies will attend and participate in the kick-off meeting and in the mid-term and final Principal Investigator reviews to be held at DARPA. In addition, the Company will convene towards the end of the program a preliminary design review/technical interchange meeting (PDR/TIM) for the program participants involved in the THOR architecture development to evaluate the photoreceiver design and its compatibility with the network architectures in development.

1.3 Technical Discussion

Epitaxial Technologies proposes to develop a monolithic integrated photoreceiver for the THOR network that will enable the continued maturation of the network for DoD wide deployment. This technology will be based on the Company's existing long wave VCSEL and RTBT

technologies that will be vertically integrated for ultra sensitive photoreceivers. To realize this vision, Epitaxial Technologies will implement the following innovations:

1. Unique VCSEL design for high gain optical preamplification
2. RTBT based photodiode/phototransistor for low noise optical converter
3. Combination of these two technologies for monolithic photoreceiver integration

The requirements of the THOR network are very challenging, because of the need to transmit and receive optical signals through a lossy and highly variable medium. As a result, a substantial portion of the challenge falls on the photoreceiver. The incoming signal at any THOR node can be as low as 10^{-5} watt and as high as 0.5 watt. The photoreceiver must amplify and convert this signal with minimal noise and distortion. Table 1.1 shows the required link budget of a notional THOR photoreceiver. The network requirement is for input optical powers as low as –47 dBm and an output bit stream with a 5V peak-to-peak amplitude. Our overall goal is to meet this requirement with an integrated photoreceiver whose elements have the individual performance specifications shown in Table 1.1. How we will implement this is detailed in the following subsections.

Table 1.1 Required link budget of a notional photoreceiver for the THOR network

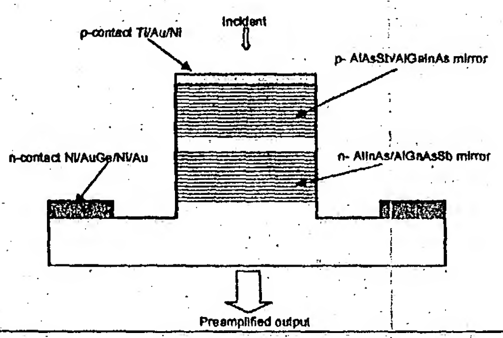
Input power= -47 dBm → Photoreceiver – THOR network requirements → Output signal = 5Vpp

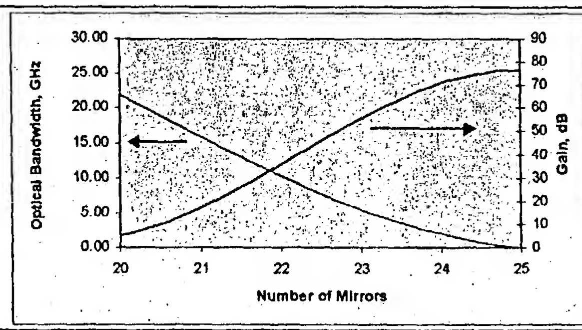
	Optical Amplifier	Photodiode optical converter	Buffer amplifier
Received power (dBm)	-47	-17	
Signal Gain (dB)	30		20
Conversion gain (V/W)		2500	
Output power (dBm)	-17		
Output Signal		.05Vpp	5 Vpp

The VCSEL optical amplifier will be based on Epitaxial Technologies' antimony based VCSEL technology. The VCSEL device structure, depicted in Figure 1.4, have Sb/As based mirrors with high differential refractive indices, low conduction and valence band offsets and low resistances. The innovative AlAsSb/AlGaInAs stack for the p-type mirror and AlInAs/AlGaAsSb for the n-type have high differential refractive indices of 0.46, low bandgap discontinuities and reduce the number of layers in the mirror stack by a factor of 2, thereby also reducing the resistivity. In our design, the active layers will be the only ones to absorb the incident optical signal. They are based on multiple period quantum wells of AlInA/GaInAs designed with thicknesses for optimum gain at 1.55 µm. In a planar VCSEL design, the AlInAs can be oxidized for current confinement instead of mesa etching.

The sensitivity of an optical preamplifier based on this VCSEL design will depend on the optical gain, bandwidth and noise figure. These in turn depend on design parameters such as the active layer length, the mirror dimension and number of mirror periods. The dependency of the gain, for example, on one of these design parameters is shown in Figure 1.4. A higher number of mirrors results in higher gain and in a lower optical bandwidth, which is important for the VCSEL amplifier so that it can also act as a filter, thereby minimizing the amplifier noise. Therefore, we will use mirror periods of about 22 in our VCSEL amplifier design to achieve the required gain of ~30 dB and optical bandwidth of 0.1 –0.6 nm (10 – 100 GHz).

The optical converter will be based on Epitaxial Technologies' resonant bipolar technology. The approach here is to use a single material structure to integrate all the active elements of the optical converter such as the PIN diode using the p-n junction of the RTBT and the transimpedance amplifier (TIA) and the buffer amplifier using the HBT part of the structure. In addition, the resonant tunneling diode (RTD) structure can be used for a number of important functions, such as low power switches, oscillators for clock generation and for parametric amplification, if additional gain is required. In particular, the switches can be used to implement the post conversion OOK modulation for an additional 6 dB improvement in sensitivity. Because the RTBT is a three terminal device, all this functions can be implemented without the need for circulators and isolators.





a. Schematic drawing of VCSEL preamp	b. Power gain and optical bandwidth

Figure 1.4 VCSEL amplifier structure and estimated performance

Figure 1.5 shows the basic RTBT structure. The material structures that are most optimum for the RTBT layers are InP/GaAsSb/GaInAs as HBT and AlAsSb/GaInAs/AlSbAs as RTD. The former yield HBTs with the highest gain and frequency response and power performance because of the high hole mobility in the base, the low emitter resistance and the high collector breakdown voltage enabled by this combination of heterojunctions. The latter results in large peak-to-valley ratios (PVR), low valley currents, and high current density because of its large conduction band discontinuity (ΔEc). Large negative resistance and current density are required to reduce power consumption, but the frequency of operation depends on high current-to-capacitance ratio of the RTD. With this material structure, PIN junctions, HBTs, RTDs can be produced and used to implement circuits like PIN detectors, amplifiers, oscillators and switches all with the same material.

The performance of an optical converter based on the RTBT technology will depend on the conversion efficiency of the photodetector and the gain of the amplifiers that can be implemented with the RTBT. The photodetector must have the highest responsivity which in turn depends on

the quality of the GaInAs absorption layer and its thickness. The transimpedance amplifier (TIA) must have a high transimpedance and a high enough bandwidth for the data bit rate (2.5 Gb/s). The transimpedance, gain and bandwidth of a TIA are determined by the feedback resistance. Therefore the TIA must have a high feedback resistance which in turn requires that the RTBT has a high gain and high bandwidth in order for the TIA to have a high bandwidth.

Epitaxial Technologies' RTBT technology already has the performance to meet the requirements of a 2.5 Gb/s bit rate data transmission system. The photodetector shown in Figure 1.6 has a responsivity of 2 A/W. With a feedback resistance of 1250 ohm in the transimpedance circuit, this corresponds to a conversion gain of 2500 V/W as required by the link budget of Table 1.1.

The RTBT shown in Figure 1.6 has current gain of 50 in the HBT portion of the I-V characteristics, while the RTD portion has a PVR of 6. In addition, a 5μm x 5μm device has an f_T of 50 GHz, while we project an f_T of 150-200 GHz for 1.5 μm to 6 μm emitters. The transistor bandwidth of the large HBTs is wide enough for the 2.5 Gb/s TIA. As the network speed requirements increase, a clear path to maturation of the proposed technology is through minor reduction in RTBT sizes and through a second design iteration to increase the bandwidth and bit rate of the receiver.

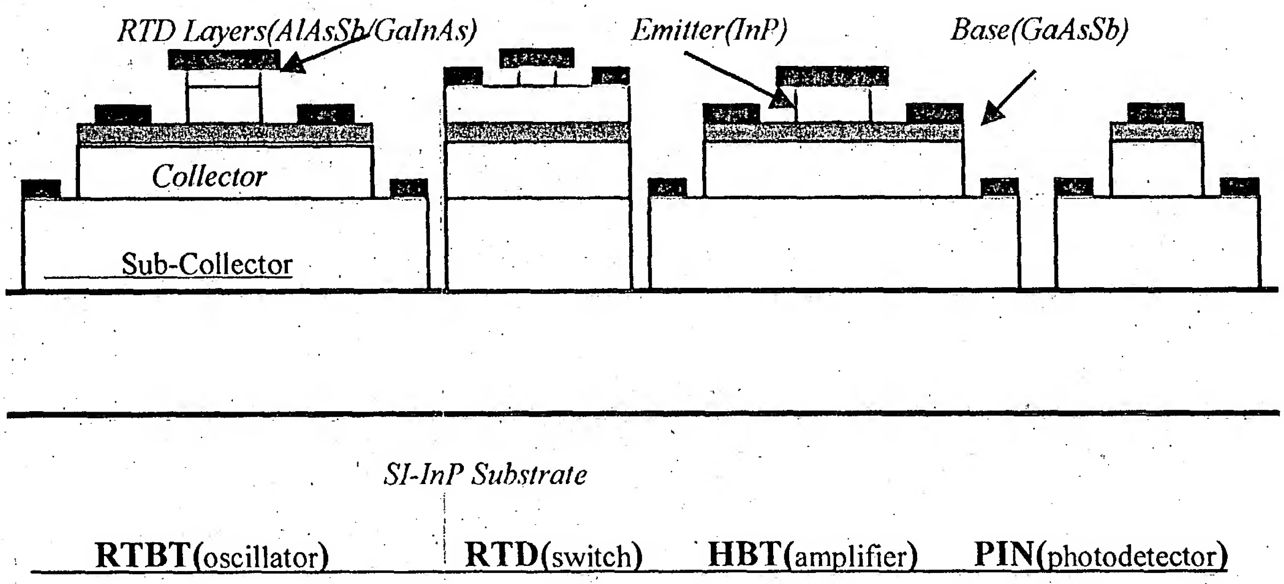


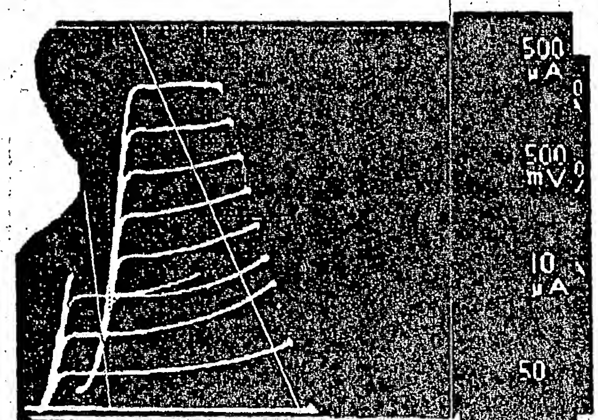
Figure 1.5 RTBT optical converter structure

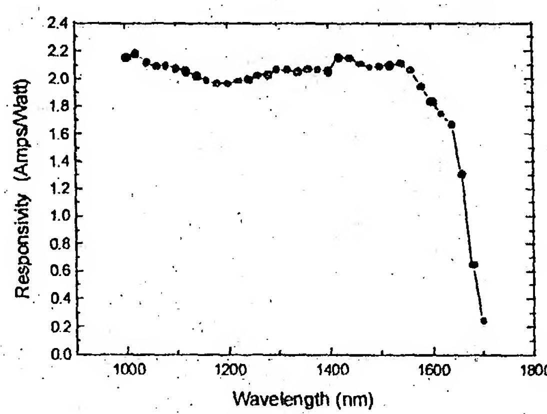
The buffer amplifier can be easily implemented using the RTBTs which has an f_{max} of 45 GHz and already is capable of power gain of 18 dB at 2.5 GHz. Therefore, a two-stage design should easily yield the required 20 dB gain. Appropriate choice of the dimension of the transistors in the output stage can be used to provide the required output drive into the modulator circuitry.

In designing the optical converter, which combines the photodetector with the TIA, we will investigate various circuit design topologies involving different combinations of photodetector and TIA. For example, instead of a single photodetector, two can be used to further minimize the optical converter noise. However, this will optimally require an additional optical preamplifier, which can be easily implemented using the photoreceiver array approach. We will also explore

various TIA topologies such as the current feedback, voltage feedback and the reactive feedback techniques to decide which provides the best combination of gain and noise performance.

To optimize the RTBT technology specifically for the THOR network requirements, we will design and purchase a mask set to tweak the processes to fabricate RTDs, HBTs, RTBTs, and PIN diodes using a single RTBT heterostructure. The mask set will consists of various sizes of RTDs, HBTs, and RTBTs to facilitate the device modeling. We will also use emitter sizes as small as 0.5µm to achieve f_T greater than 300 GHz. The mask set will also include process control monitoring and other test structures. All the pads of the devices will be selected to have appropriate pitch to facilitate microwave measurements. In the fabrication of these devices, extreme care will be taken to minimize coupling and leakage paths between devices. We will characterize both dc and RF performances of the devices. From the measured data, we will develop models of RTD, HBT, and PIN diodes. The models for the RTBT will be developed for different biasing conditions (negative resistance region, saturation region etc.).





a. RTBT b. Photodetector

Figure 1.6 Performance of some individual RTBT optical converter elements

We have shown that all the individual elements of the monolithic integrated photoreceiver with performance suitable for the THOR network can be implemented using Epitaxial Technologies' long wavelength VCSEL and RTBT technologies. The proposed effort for this phase is to optimize the performance of the individual elements and produce prototype photoreceiver elements for the simulation and design of the integrated photoreceiver. Once the individual photoreceiver elements have been developed during the first part of the first Phase of this program, they will be thoroughly characterized to determine equivalent circuit models and circuit parameters. The data so obtained will be used to design an integrated photoreceiver using photonic design software such as Crosslights' PICS3D for the VCSEL design and Spice, Agilent ADS and Photoss for the analog, digital and optical system design respectively.

The specific design optimization of the integrated photoreceiver will include reducing the gain of the VCSEL amplifier by reducing the number of mirror stacks which will simplify the processing, increase yields and reduce the photoreceiver costs. This reduction in gain can then be balanced by designing the optical converter and the subsequent stages to provider higher gain. Another design issue is the integration of the VCSEL amplifier with the detector. Here, special

attention will be paid to the coupling of the preamplified optical signal into the detector. The exit mirror will be designed to maximize optical output. The semiconductor layer between the VCSEL amplifier and the photodetector will be chosen to have the right refractive index for optimum coupling. Alternatively, the VCSEL will be grown separately on a different wafer and then bonded onto the RTBT wafer with an intervening layer such as ITO/SiO_x that have low refractive indices and will enable maximum optical coupling.

The proposed ultrasensitive photoreceiver will meet the requirements of a 2.5 Gb/s THOR network. The extension of the network for DoD wide deployment and the future demand for more bandwidth intensive services will necessitate the migration of the THOR network to higher bit rates. While it is not clear at the moment whether higher bit rates than 2.5 GB/s will be possible with the THOR network, it is quite likely suitable architectures and underlying technologies will be developed to enable this upwards migration. This technology maturation issue needs to be addressed by each program participant to ensure the most affordable and least disruptive extension and upgrading of the THOR network. Epitaxial Technologies believes the long wavelength VCSEL and RTBT technologies it proposes to use to develop the integrated photoreceiver will also be capable of producing optical and electronic devices and circuits at bit rates up to 40 Gb/s and beyond. Therefore, the Company will undertake to evaluate how its technologies will contribute to the successful technology maturation of the THOR network. To do this, we will investigate the limits of the photoreceiver bandwidths and how they can be extended through additional design iterations in the second and third phase of the program. The device and circuit optimization that will be undertaken during the first phase will yield components with bit rates greater than 2.5 Gb/s. By adding designs for higher bit rate circuits such as at 10 and 40 Gb/s, our proposed ultrasensitive photoreceiver will be ready for the next evolution of the THOR network and also other DoD applications.

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